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Citation: Kahwash, Fadi, Shyha, Islam and Maheri, Alireza (2015) Modelling of cutting fibrous composite materials: current practice. Procedia CIRP, 28. pp. 52-57. ISSN 2212-8271

Published by: Elsevier

URL: <http://dx.doi.org/10.1016/j.procir.2015.04.010>
<<http://dx.doi.org/10.1016/j.procir.2015.04.010>>

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Modelling of cutting fibrous composite materials: current practice

F. Kahwash^a, I. Shyha^{a,b,*}, A. Maheri^a^aFaculty of Engineering and Environment, Northumbria University, Ellison Place, Newcastle upon Tyne, NE1 8ST, UK.^bProduction Engineering Department, Faculty of Engineering, Alexandria University, 21544 Alexandria, Egypt* Corresponding author. Tel.: +44-191-243-7834; fax: +44-191-227-3598. E-mail address: islam.shyha@northumbria.ac.uk**Abstract**

Using fibre reinforced polymers (FRP) is increasing across many industries. Although FRP are laid-up in the near-net shape, several cutting operations are necessary to meet quality and dimensional requirements. Modelling of cutting is essential to understand the physics of the cutting phenomena and to predict quality and cost of products. This paper aims at reviewing the current practice in modelling of cutting FRP including analytical, numerical, mechanistic and empirical approaches, with emphasis on analytical models of cutting forces and delamination. Processes detailed include orthogonal cutting, drilling, milling and turning. Finally, advances in machining of metal-composite stacks are presented.

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Selection and peer-review under responsibility of the International Scientific Committee of the “3rd CIRP Global Web Conference” in the person of the Conference Chair Dr. Alessandra Caggiano.

Keywords: Fibre reinforced plastics; Analytical modelling; Cutting forces; Meshfree methods; Metal-composite stacks

1. Introduction

The use of composite materials is increasing in many industries such as aerospace, automotive and sports equipment due to their superior properties to metallic materials. Fibre reinforced polymers (FRP) are the most widely used composites with carbon or glass as reinforcement constituent. Machining operations are required to obtain the necessary shape, dimensions and surface quality of the composites parts. Modelling of cutting is important for predicting the quality and cost of manufacturing processes by calculating fundamental process outputs such as cutting forces, stresses and strains and/or industry relevant outputs such as tool wear and surface quality. Modelling of cutting can be done using one of four main approaches namely, analytical, numerical, mechanistic and empirical. Selecting one approach over others depends on the type of input data, available computation resources, the desired output variables and the required level of accuracy. Modelling of cutting composites is challenging task due to (i) the composites' anisotropic and heterogeneous nature (ii) the inherent complexity of the cutting process.

This paper therefore, discusses the applications of the different modelling approaches to conventional cutting

processes of composites with emphasis on analytical modelling of cutting forces and delamination.

2. Modelling of FRP Cutting

Most of the research on cutting composites has adopted the empirical approach, which is very useful in observing the process variables and their relative importance however, theoretical studies are needed to understand the physics of FRP cutting [1].

2.1. Orthogonal cutting

Orthogonal cutting is the most studied process theoretically and experimentally because it is 2D problem [2] thereby, it is easier to study. Majority of the analytical studies focused on calculating cutting forces. Takeyama and Iijima [3] proposed a model based on the minimum energy principle to predict the cutting and thrust forces. The model agreed fairly well with experiments, despite being criticised because it does not account for the effect of machining direction and for the lack of transparency in obtaining the shear angle values [4]. Subsequently, it was observed by Bhatnagar et al. [5] that crack propagation happens along the fibre

direction in the range 90° to 180° , thus they developed a cutting force model based on Merchant's principle of minimum energy by substituting the shear plane angle with the fibre orientation angle. The study confirmed the significance of fibre orientation and cutting direction on cutting forces values and on tool-chip friction on the rake face. Later, Zhang [6, 7] proposed new analytical model by dividing the cutting domain into three regions (i) chipping region (region 1) in front of the rake face of the tool, (ii) pressing region (region 2) under the nose of the tool and (iii) bouncing region (region 3) below the relief face of the tool as shown in Fig. 1. Cutting and feed forces were calculated in each region and then superimposed to calculate the total cutting forces. The model was built for fibre orientation less than 90° since beyond that; additional damage mechanisms exist that are not captured by the model.

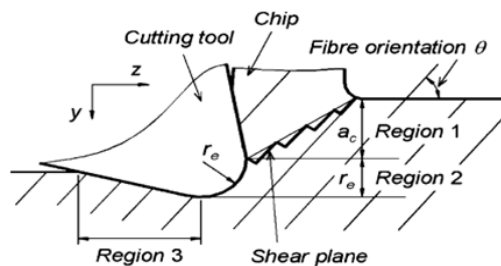


Fig. 1. Deformation zones in orthogonal cutting of FRPs [6]

Later, Sahraie-Jahromi and Bahr [8] extended Zhang's model to the range 90° to 180° by proposing additional damage mechanisms for that region. They identified three main damage mechanisms namely; fibre micro-buckling, fibre-matrix de-bonding and fibre bending then calculated the cutting and thrust forces accordingly and compared it with experiments. The accuracy of predictions was limited due to the mismatch in materials properties and boundary conditions between the model and experiments and due to non-uniform distribution of fibres among the matrix.

Subsurface stresses were studied analytically by Gururaja and Ramulu [1] who proposed a model to calculate stress fields in the subsurface area after orthogonal cutting of FRPs by modelling the effect of the cutting tool as line load profile inclined with an angle. The effect of anisotropy on stress fields varied with changes in volume fraction and fibre orientation.

Numerical methods can have more predictive power than analytical because it is possible to include more variables in the study and to account for more failure mechanisms [9]. Finite element methods (FEM) have been applied extensively to study composites machining; refer to Dandekar and Shin's review [9]. FEM models require defining material model, element failure criteria for chip formation and tool-chip contact models.

Moreover, using FEM in machining requires remeshing because of the large deformations and severe element distortion. Remeshing is time consuming, can be complicated for 3D problems and for every iteration, studied quantities should be projected on the new mesh leading to gradual accumulation of error [10]. Moreover, FEM is not well suited for modelling discontinuities if they do not coincide with elements' boundaries [11].

Meshfree methods are group of numerical methods for solving partial differential equations in which the studied domain is discretised through non-connected nodes rather than connected elements. This eliminates part or whole of the meshing process [12]. Some advantages in using meshfree methods in machining problems are (i) the ability to simulate large deformations and discontinuities without the need for remeshing, (ii) the flexibility in adding or removing nodes without worry about their relation to neighbouring nodes [12], (iii) better integration with CAD/CAE/CAM software [10], (iv) elimination of separation criteria and arbitrary contact conditions [13]. Meshfree methods include: smoothed particle hydrodynamics, finite pointset method, element-free Galerkin, reproducing kernel particle, moving least square interpolations and constrained natural element method. These methods have been applied to solid mechanics problems [10, 12, 14, 15], machining of metals [16-24], as seen in Fig. 2 and to fracture of composite materials [11, 25, 26].

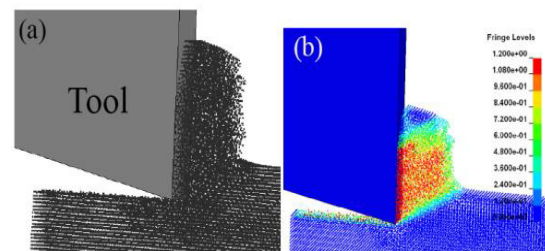


Fig. 2. Orthogonal cutting simulation using smoothed particle hydrodynamics: (a) 3D view and (b) effective plastic strain [18]

Few empirical models have also been developed for orthogonal cutting of FRPs, one to calculate cutting forces [27], another to evaluate the effect of tool wear on cutting forces [28] where it was found that tool wear has significant effect on cutting force values. In addition, cutting mechanisms identification study was conducted in [29] by analysing frequency of measured force signals. The study showed that signal characteristics differ for different cutting mechanisms.

2.2. Drilling

Drilling is the most widely used cutting operation for composite materials because of the need for joining structures [30], therefore considerable amount of literature exists with comprehensive review papers [31-33]. Delamination is the major concern in drilling FRPs,

it results mainly from thrust force pushing the last uncut lamina via the chisel edge causing interlaminar failure as seen in Figure 3. Delamination is initiated when the thrust force exceeds a critical value also called critical thrust force (CTF) and most of the modelling efforts were directed towards calculating this value. The earliest CTF model was developed by Hocheng and Dharan [34] then, seminal contribution was made in the work of Hocheng and Tsao [30, 35-39]. Based on linear elastic fracture mechanics approach, they developed several models for special drill bits such as candle stick drill, saw drill and core drill that are designed to reduce delamination by distributing the thrust force away from the chisel edge onto the periphery of the tool. Their other work includes critical thrust force models taking the effect of tool eccentricity, using pilot holes and drilling with backup plate. More recently Rahmé et al. [40] studied the effect of loading assumption on the critical thrust force model as a function of the number of delaminated plies. Thrust force was modelled as concentrated, uniformly distributed, triangular, disc and concentrated with uniform distribution; the latter assumption was found to be closest to experiments.

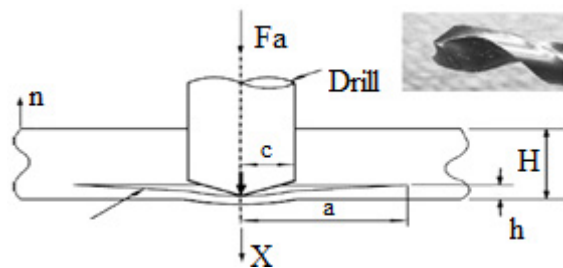


Fig. 3. Delamination onset while drilling with twist drill [39]

FEM studies of drilling were conducted to study the effect of cutting parameters on the thrust force, v torque [41] and to study delamination [42] where the numerical model was compared with the existing analytical models. It was found that both approaches do not capture the effect of parameters variation on delamination onset which necessitates further development of both modelling approaches.

The only mechanistic model for drilling was developed by Zhang et al. [43] to predict average thrust force and torque in vibration drilling of FRPs. The model required one test to determine the shear flow stress as an input. The results showed acceptable agreement between model predictions and experiments. Delamination was also investigated experimentally by Davim and Reis [44] as a function of tool geometry and cutting parameters. The study showed positive correlation between cutting parameters and delamination and that cutting speed is more statistically significant. However, this result contradicted the findings of Tsao

and Ho-cheng [45, 46] who developed empirical CTF models for step drill and candle stick drill using Taguchi design and artificial neural networks. They found that feed rate and drill diameter were the most statistically significant factors. Furthermore, delamination-free step-drilling was achieved using low feed rates and high spindle speeds.

2.3. Milling

Milling is usually used in cutting FRP as corrective end machining operation or to give the required dimensional accuracy and produce high quality surfaces [47]. Delamination is also a concern during milling operations, it was studied by Hintze and Hartmann [48] during contour milling of CFRP. An analytical model for predicting delamination at the top layer was proposed by taking into account the geometric and mechanical properties of the laminate. The cutting force was found to cause the fibres to bend rather than fracture causing delamination. Mechanistic force model was developed by Karpat et al. [49, 50] who started by conducting milling tests with constant cutting speed. Cutting speed was deemed less significant compared with feed rate, which agreed with the findings in [51, 52]. A dynamic force model was then developed with force coefficients approximated to Sine function of fibre orientation and was found to have reasonable agreement with results. Karpat et al. also investigated the quality of the machined surfaces and found the locations of maximum cutting forces coincided with locations of largest delamination. Mechanistic model for helical milling was developed by Kalla et al. [53] for predicting cutting forces of uni/multi-directional CFRP for fibre orientation between 0-180°. The cutting force coefficients required in such models were obtained from artificial neural network (ANN) database. The relationship between the cutting parameters with the cutting forces and surface roughness [51, 52] was studied empirically and found that cutting forces increased with feed rate and decreased with cutting velocity. Sreenivasulu [54] conducted experimental study on the effect of cutting parameters on the delamination and surface roughness of GFRP during end milling using Taguchi design and neural networks. The cutting speed and depth of cut were found to be statistically significant parameters affecting delamination and surface roughness.

2.4. Turning

Very limited work was done on modelling of turning composite materials with majority of the studies using the experimental approach. Chang [55] developed force model for turning GFRP using chamfered tool. The model was experimentally verified. Cutting forces and

temperatures were investigated as a function to cutting tool material and geometry. Tool material was found to be statistically significant factor affecting cutting forces (K carbide tools yielded lower cutting forces than P carbide tools). Palanikumar [56-58] developed empirical models to predict surface roughness and tool wear when turning GFRP. Higher surface roughness values were observed with increasing feed rate, fibre orientation angle, while it decreased with higher cutting speed and depth of cut. With regards to tool wear, cutting speed was found to be the most significant factor followed by the feed rate. Hanfi et al. [59] developed a fuzzy rule-based model and response surface method-based model to predict cutting forces and power using control variables including cutting speed, feed and depth of cut. Gill et al. [60] also developed an empirical model to study the effect of cutting conditions and tool geometry on the cutting forces during turning of unidirectional GFRP lamina. Depth of cut had the most statistical significance on cutting forces.

3. Cutting metal-composite stacks

The usage of multi-layer materials is increasing in aerospace industry [61] especially in parts with high mechanical loads [62]. This is due to their high strength to weight ratio, superior fatigue performance and the wide range of functionality that every layer contribute to the overall properties of the stack [63, 64]. Different layers are joined by riveting or bolting, which necessitates generating holes into the different layers to the required dimensional tolerances. This is done mostly by drilling, but also by helical milling [65] and rotary ultrasonic machining [66]. There are three popular material combinations namely, CFRP/Al [67-69], CFRP/Ti [65, 66, 70-73] and Ti/CFRP/Al [61, 62, 67].

Limited theoretical modelling attempts were made when cutting metal-composite stacks. Roudgé et al. [74] introduced stacking order indicator which quantified the effect of stacking order on the machinability of the stack and quality indicator by aggregating all relevant quality measures with different weighting factors. Qi et al. [69] formulated CTF model when drilling CFRP/Al stack. The stacking order was changed and models developed for both cases. When CFRP was drilled last, the CTF was function of proportional coefficient of concentrated force, the critical energy release rate and the material coefficient of the uncut laminates. When Al was drilled last, CTF was affected by the assumed edge conditions, furthermore, a critical thickness of Al plate was calculated after which delamination did not occur. Vijayaraghavan and Dornfeld [64] presented a framework for FEM modelling of multi-layer materials that can be used to develop an accurate and practical drilling simulation tool. Matsumura and Tamura [75]

developed a mechanistic model to predict cutting forces and chip flow in drilling multi-layer stacks by assuming that the oblique cutting process is a series of orthogonal cutting processes with different tool geometries. Material properties coefficients were experimentally obtained and model was verified as shown in Fig. 4.

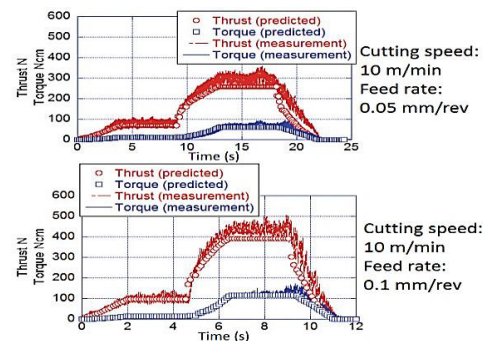


Fig. 4. Predicted vs. measured torque and thrust force values [75]

4. Conclusions

Current practices in modelling conventional cutting of FRP were presented in this paper. It is noted that orthogonal cutting has the most coverage in the literature due to its relative simplicity. Analytical models for orthogonal cutting are simple and discard much of the cutting phenomena, whereas more sophisticated models have been constructed using numerical approach. Drilling is investigated extensively, with concentration on delamination, especially using analytical models. Several critical thrust force models have been developed for special drill bits and delamination-free assistive techniques such as pilot holes and drilling with backup plate. Cutting forces, delamination and surface roughness are examined as function of cutting parameters for contour, helical and end milling of FRPs using the four modelling approaches. Modelling research on turning was found scarce and focused on cutting forces and surface quality. Metal composite stacks are becoming popular in aerospace industry and there is a need for generating holes through the different layers in a single shot for joining purposes. This is mainly achieved by drilling, but also by helical milling and rotary ultrasonic machining. Most of the research is experimental with recent and few attempts in analytical force modelling.

Despite the noticeable progress documented above, more modelling research is still needed. In analytical modelling, 3D models and models that include thermo-mechanical effects are absent. In numerical modelling, accurate representation of multi-scale failure mechanisms, large deformations and discontinuities are still challenging tasks, in addition to the high computational cost. Improvements on mechanistic

models can be achieved by reducing the number of required tests to obtain the coefficients.

Authors believe that current literature metal cutting modelling might give useful insights into the development of more accurate analytical models of composites cutting. Emerging applications of multi-scale modelling and meshfree methods into machining and fracture problems provide a good opportunity to improve the accuracy of the numerical approach.

References

- [1] Gururaja, S. and Ramulu, M., 2010. Analytical formulation of subsurface stresses during orthogonal cutting of FRPs, *Composites Part A: Applied Science and Manufacturing*, 41, pp. 1164-1173.
- [2] Markopoulos, A. P., 2013. Cutting Mechanics and Analytical Modeling, in *"Finite Element Method in Machining Processes"*, edSpringer: pp. 11-27.
- [3] Takeyama, H. and Iijima, N., 1988. Machinability of Glassfiber Reinforced Plastics and Application of Ultrasonic Machining, *CIRP Annals - Manufacturing Technology*, 37, pp. 93-96.
- [4] Gordon, S. and Hillery, M., 2003. A review of the cutting of composite materials, *Proceedings of the Institution of Mechanical Engineers, Part L: Journal of Materials Design and Applications*, 217, pp. 35-45.
- [5] Bhatnagar, N., Ramakrishnan, N., Naik, N. K., and Komanduri, R., 1995. On the machining of fiber reinforced plastic (FRP) composite laminates, *International Journal of Machine Tools and Manufacture*, 35, pp. 701-716.
- [6] Zhang, L., Zhang, H., and Wang, X., 2001. A force prediction model for cutting unidirectional fibre-reinforced plastics,
- [7] Zhang, L. C., 2009. Cutting composites: A discussion on mechanics modelling, *Journal of Materials Processing Technology*, 209, pp. 4548-4552.
- [8] Sahraie Jahromi, A. and Bahr, B., 2010. An analytical method for predicting cutting forces in orthogonal machining of unidirectional composites, *Composites Science and Technology*, 70, pp. 2290-2297.
- [9] Dandekar, C. R. and Shin, Y. C., 2012. Modeling of machining of composite materials: A review, *International Journal of Machine Tools and Manufacture*, 57, pp. 102-121.
- [10] Huerta, A., Belytschko, T., Fernández-Méndez, S., and Rabczuk, T., "Meshfree methods," in *Encyclopedia of Computational Mechanics*, E. Stein, R. de Borst, and T. J. R. Hughes, Eds., ed: John Wiley & Sons, Ltd., 2004.
- [11] Barbieri, E., "Meshfree methods for the analysis of composite materials," University of Bath, 2010.
- [12] Liu, G.-R., *Meshfree methods: moving beyond the finite element method*: CRC press, 2010.
- [13] Arrazola, P. J., Özel, T., Umbrello, D., Davies, M., and Jawahir, I. S., 2013. Recent advances in modelling of metal machining processes, *CIRP Annals - Manufacturing Technology*, 62, pp. 695-718.
- [14] Liew, K., Ng, T., and Wu, Y., 2002. Meshfree method for large deformation analysis—a reproducing kernel particle approach, *Engineering Structures*, 24, pp. 543-551.
- [15] Nguyen, V. P., Rabczuk, T., Bordas, S., and Duflot, M., 2008. Meshless methods: a review and computer implementation aspects, *Mathematics and Computers in Simulation*, 79, pp. 763-813.
- [16] Zahedi, A., Li, S., Roy, A., Babitsky, V., and Silberschmidt, V. V., "Application of Smooth-Particle Hydrodynamics in Metal Machining," in *Journal of Physics: Conference Series*, 2012, p. 012017.
- [17] Limido, J., Espinosa, C., Salaün, M., and Lacombe, J.-L., 2007. SPH method applied to high speed cutting modelling, *International journal of mechanical sciences*, 49, pp. 898-908.
- [18] Villumsen, M. F. and Fauerholdt, T. G., 2008. Simulation of metal cutting using smooth particle hydrodynamics, *LS-DYNA. Anwenderforum, Bamberg*, pp. 17-36.
- [19] Bagci, E., 2011. 3-D numerical analysis of orthogonal cutting process via mesh-free method, *Int. J. the Physical Sciences*, 6, pp. 1267-1282.
- [20] Heisel, U., Zaloga, W., Krivoruchko, D., Storchak, M., and Goloborodko, L., 2013. Modelling of orthogonal cutting processes with the method of smoothed particle hydrodynamics, *Production Engineering*, pp. 1-7.
- [21] Madaj, M. and Piška, M., 2013. On the SPH Orthogonal Cutting Simulation of A2024-T351 Alloy, *Procedia CIRP*, 8, pp. 152-157.
- [22] Eberhard, P. and Gaugele, T., 2013. Simulation of cutting processes using mesh-free Lagrangian particle methods, *Computational Mechanics*, 51, pp. 261-278.
- [23] Uhlmann, E., Gerstenberger, R., and Kuhnert, J., 2013. Cutting Simulation with the Meshfree Finite Pointset Method, *Procedia CIRP*, 8, pp. 390-395.
- [24] Illoul, L. and Lorong, P., 2011. On some aspects of the CNEM implementation in 3D in order to simulate high speed machining or shearing, *Computers & Structures*, 89, pp. 940-958.
- [25] Barbieri, E. and Meo, M., 2009. A meshfree penalty-based approach to delamination in composites, *Composites Science and Technology*, 69, pp. 2169-2177.
- [26] Barbieri, E. and Meo, M., 2011. A Meshless Cohesive Segments Method for Crack Initiation and Propagation in Composites, *Applied Composite Materials*, 18, pp. 45-63.
- [27] Caprino, G. and Nele, L., 1996. Cutting Forces in Orthogonal Cutting of Unidirectional GFRP Composites, *Journal of Engineering Materials and Technology*, 118, pp. 419-425.
- [28] Caprino, G., De Iorio, I., Nele, L., and Santo, L., 1996. Effect of tool wear on cutting forces in the orthogonal cutting of unidirectional glass fibre-reinforced plastics, *Composites Part A: Applied Science and Manufacturing*, 27, pp. 409-415.
- [29] Ramulu, M., Kim, D., and Choi, G., 2003. Frequency analysis and characterization in orthogonal cutting of glass fiber reinforced composites, *Composites Part A: Applied Science and Manufacturing*, 34, pp. 949-962.
- [30] Hocheng, H. and Tsao, C. C., 2006. Effects of special drill bits on drilling-induced delamination of composite materials, *International Journal of Machine Tools and Manufacture*, 46, pp. 1403-1416.
- [31] Abrão, A. M., Faria, P. E., Rubio, J. C. C., Reis, P., and Davim, J. P., 2007. Drilling of fiber reinforced plastics: A review, *Journal of Materials Processing Technology*, 186, pp. 1-7.
- [32] Khashaba, U., 2013. Drilling of polymer matrix composites: A review, *Journal of Composite Materials*, 47, pp. 1817-1832.
- [33] Singh, A. P., Sharma, M., and Singh, I., 2013. A review of modeling and control during drilling of fiber reinforced plastic composites, *Composites Part B: Engineering*, 47, pp. 118-125.
- [34] Ho-Cheng, H. and Dharan, C., 1990. Delamination during drilling in composite laminates, *Journal of Engineering for Industry*, 112, pp. 236-239.
- [35] Tsao, C. C. and Hocheng, H., 2003. The effect of chisel length and associated pilot hole on delamination when drilling composite materials, *International Journal of Machine Tools and Manufacture*, 43, pp. 1087-1092.
- [36] Hocheng, H. and Tsao, C., 2005. The path towards delamination-free drilling of composite materials, *Journal of Materials Processing Technology*, 167, pp. 251-264.
- [37] Tsao, C. and Hocheng, H., 2005. Effect of eccentricity of twist drill and candle stick drill on delamination in drilling composite materials, *International Journal of Machine Tools and Manufacture*, 45, pp. 125-130.

- [38] Tsao, C. C. and Hocheng, H., 2005. Effects of exit back-up on delamination in drilling composite materials using a saw drill and a core drill, *International Journal of Machine Tools and Manufacture*, 45, pp. 1261-1270.
- [39] Hocheng, H. and Tsao, C. C., 2003. Comprehensive analysis of delamination in drilling of composite materials with various drill bits, *Journal of Materials Processing Technology*, 140, pp. 335-339.
- [40] Rahmé, P., Landon, Y., Lachaud, F., Piquet, R., and Lagarrigue, P., 2011. Analytical models of composite material drilling, *The International Journal of Advanced Manufacturing Technology*, 52, pp. 609-617.
- [41] Phadnis, V., Roy, A., and Silberschmidt, V., "Finite element analysis of drilling in carbon fiber reinforced polymer composites," in *Journal of Physics: Conference Series*, 2012, p. 012014.
- [42] Durão, L. M. P., de Moura, M. F. S. F., and Marques, A. T., 2008. Numerical prediction of delamination onset in carbon/epoxy composites drilling, *Engineering Fracture Mechanics*, 75, pp. 2767-2778.
- [43] Zhang, L. B., Wang, L. J., Liu, X. Y., Zhao, H. W., Wang, X., and Luo, H. Y., 2001. Mechanical model for predicting thrust and torque in vibration drilling fibre-reinforced composite materials, *International Journal of Machine Tools and Manufacture*, 41, pp. 641-657.
- [44] Davim, J. P. and Reis, P., 2003. Study of delamination in drilling carbon fiber reinforced plastics (CFRP) using design experiments, *Composite Structures*, 59, pp. 481-487.
- [45] Tsao, C. C., 2008. Prediction of thrust force of step drill in drilling composite material by Taguchi method and radial basis function network, *The International Journal of Advanced Manufacturing Technology*, 36, pp. 11-18.
- [46] Tsao, C. C. and Hocheng, H., 2008. Evaluation of thrust force and surface roughness in drilling composite material using Taguchi analysis and neural network, *Journal of Materials Processing Technology*, 203, pp. 342-348.
- [47] Teti, R., 2002. Machining of Composite Materials, *CIRP Annals - Manufacturing Technology*, 51, pp. 611-634.
- [48] Hintze, W. and Hartmann, D., 2013. Modeling of Delamination During Milling of Unidirectional CFRP, *Procedia CIRP*, 8, pp. 444-449.
- [49] Karpat, Y., Bahtiyar, O., and Değer, B., 2012. Milling Force Modelling of Multidirectional Carbon Fiber Reinforced Polymer Laminates, *Procedia CIRP*, 1, pp. 460-465.
- [50] Karpat, Y., Bahtiyar, O., and Değer, B., 2012. Mechanistic force modeling for milling of unidirectional carbon fiber reinforced polymer laminates, *International Journal of Machine Tools and Manufacture*, 56, pp. 79-93.
- [51] Davim, J. P., Reis, P., and António, C. C., 2004. A study on milling of glass fiber reinforced plastics manufactured by hand-lay up using statistical analysis (ANOVA), *Composite Structures*, 64, pp. 493-500.
- [52] Davim, J. P. and Reis, P., 2005. Damage and dimensional precision on milling carbon fiber-reinforced plastics using design experiments, *Journal of Materials Processing Technology*, 160, pp. 160-167.
- [53] Kalla, D., Sheikh-Ahmad, J., and Twomey, J., 2010. Prediction of cutting forces in helical end milling fiber reinforced polymers, *International Journal of Machine Tools and Manufacture*, 50, pp. 882-891.
- [54] Sreenivasulu, R., 2013. Optimization of Surface Roughness and Delamination Damage of GFRP Composite Material in End Milling Using Taguchi Design Method and Artificial Neural Network, *Procedia Engineering*, 64, pp. 785-794.
- [55] Chang, C.-S., 2006. Turning of glass-fiber reinforced plastics materials with chamfered main cutting edge carbide tools, *Journal of Materials Processing Technology*, 180, pp. 117-129.
- [56] Palanikumar, K., 2007. Modeling and analysis for surface roughness in machining glass fibre reinforced plastics using response surface methodology, *Materials & Design*, 28, pp. 2611-2618.
- [57] Palanikumar, K. and Paulo Davim, J., 2007. Mathematical model to predict tool wear on the machining of glass fibre reinforced plastic composites, *Materials & Design*, 28, pp. 2008-2014.
- [58] Palanikumar, K., Mata, F., and Davim, J. P., 2008. Analysis of surface roughness parameters in turning of FRP tubes by PCD tool, *Journal of Materials Processing Technology*, 204, pp. 469-474.
- [59] Hanafi, I., Khamlichi, A., Cabrera, F. M., Nuñez López, P. J., and Jabbouri, A., 2012. Fuzzy rule based predictive model for cutting force in turning of reinforced PEEK composite, *Measurement*, 45, pp. 1424-1435.
- [60] Gill, S., Gupta, M., and Satsangi, P. S., 2013. Prediction of cutting forces in machining of unidirectional glass fiber reinforced plastics composite, *Frontiers of Mechanical Engineering*, 8, pp. 187-200.
- [61] Shyha, I., Soo, S. L., Aspinwall, D. K., Bradley, S., Dawson, S., and Pretorius, C. J., 2010. Drilling of titanium/CFRP/aluminium stacks, *Key Engineering Materials*, 447, pp. 624-633.
- [62] Shyha, I. S., Soo, S. L., Aspinwall, D. K., Bradley, S., Perry, R., Harden, P., *et al.*, 2011. Hole quality assessment following drilling of metallic-composite stacks, *International Journal of Machine Tools and Manufacture*, 51, pp. 569-578.
- [63] Fail Safe Drilling of CFRP/Titanium and/Aluminium Stack with H8 Quality for Aerospace Applications, *SAE Technical Paper*, 2013.
- [64] Vijayaraghavan, A. and Dornfeld, D. A., 2005. Challenges in Modeling Machining of Multilayer Materials,
- [65] Denkena, B., Boehnke, D., and Dege, J. H., 2008. Helical milling of CFRP-titanium layer compounds, *CIRP Journal of Manufacturing Science and Technology*, 1, pp. 64-69.
- [66] Cong, W. L., Pei, Z. J., Deines, T. W., Liu, D. F., and Treadwell, C., 2013. Rotary ultrasonic machining of CFRP/Ti stacks using variable feedrate, *Composites Part B: Engineering*, 52, pp. 303-310.
- [67] Brinksmeier, E. and Janssen, R., 2002. Drilling of Multi-Layer Composite Materials consisting of Carbon Fiber Reinforced Plastics (CFRP), Titanium and Aluminum Alloys, *CIRP Annals - Manufacturing Technology*, 51, pp. 87-90.
- [68] Zitoun, R., Krishnaraj, V., and Collombet, F., 2010. Study of drilling of composite material and aluminium stack, *Composite Structures*, 92, pp. 1246-1255.
- [69] Qi, Z., Zhang, K., Li, Y., Liu, S., and Cheng, H., 2014. Critical thrust force predicting modeling for delamination-free drilling of metal-FRP stacks, *Composite Structures*, 107, pp. 604-609.
- [70] Ramulu, M., Branson, T., and Kim, D., 2001. A study on the drilling of composite and titanium stacks, *Composite Structures*, 54, pp. 67-77.
- [71] Kim, D. and Ramulu, M., 2004. Drilling process optimization for graphite/bismaleimide-titanium alloy stacks, *Composite Structures*, 63, pp. 101-114.
- [72] Poutord, A., Rossi, F., Poulachon, G., M'Saoubi, R., and Abrivard, G., 2013. Local Approach of Wear in Drilling Ti6Al4V/CFRP for Stack Modelling, *Procedia CIRP*, 8, pp. 316-321.
- [73] Isbilir, O. and Ghassemieh, E., 2013. Comparative study of tool life and hole quality in drilling of cfrp/titanium stack using coated carbide drill *Machining Science and Technology*, 17, pp. 380-409.
- [74] Roudgé, M., Cherif, M., Cahuc, O., Darnis, P., and Danis, M., 2008. Multi-layer Materials. Qualitative Approach of the Process, *International Journal of Material Forming*, 1, pp. 949-952.
- [75] Matsumura, T. and Tamura, S., 2013. Cutting Force Model in Drilling of Multi-layered Materials, *Procedia CIRP*, 8, pp. 182-187.